BOREHOLE CONDUCTIVITY PROFILER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of the filing of U.S. Provisional Patent Application Serial No. 60/416,692, entitled "Borehole Conductivity Profiler," filed on October 8, 2002, and the entire specification thereof is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention (Technical Field):

The present invention relates to measuring the hydraulic conductivity of layers of the Earth's subsurface, and particularly to an apparatus and method, deploying a flexible everting liner, for providing a continuous direct measurement of the location and flow rate of geological fractures and permeable beds intersecting a borehole.

Background Art:

Many kinds of measurements may be made to assess the characteristics of fluid flow paths in the Earth's subsurface. Most measurements are made in a borehole drilled into the geologic formations of interest. The common borehole is measured with a variety of "logging" techniques to locate fractures, to measure flow velocities in the hole, to measure the temperature effects of flowing water, and to identify potential flow paths such as permeable beds with unique measurable properties. Known measurement techniques typically involve acoustics, electrical resistivity, video scans, natural radiation detection, and induced radiation. Many of these measurements using current techniques are only indirectly related to the specific flow

characteristics desired. Other measurement approaches for flow path assessments involve the use of "packers": single, double, or more, inflatable bladders which are used to isolate a portion of the hole. The isolated portion, comprising only a section of the vertical extent of the borehole, is then pumped to assess the flow from, or into, the hole wall under specific driving conditions.

It is desirable to have an improved mode for measuring hydraulic conductivity and related characteristics more directly. The present invention does so by deploying a special liner apparatus down the borehole. Everting liner technology is best described in patents previously issued to the inventor of the present application. These patents are U.S. Patent No. 6,298,920 issued October 9, 2001; U.S. Patent No. 6,283,209 issued September 4, 2001; U.S. Patent No. 6,244,846 issued June 12, 2001; and U.S. Patent No. 6,026,900 issued February 22, 2000. Beneficial reference may be made to these patents, and their teachings are hereby incorporated by reference.

SUMMARY OF THE INVENTION (DISCLOSURE OF THE INVENTION)

A method is described of using an everting borehole liner to perform fluid conductivity measurements in materials surrounding a pipe, tube, or conduit, such as a borehole below the surface of the Earth. A flexible liner is everted (turned inside out) into the borehole with an internal pressurized fluid. As the liner displaces the ambient fluid in the borehole into the surrounding formation, the rate of descent of the liner is recorded. As the impermeable liner covers the flow paths in the wall of the hole, the descent rate slows. From the measured descent rate, the flow rates out of discrete sections of the borehole are determined.

There is provided according to the invention a method of determining hydraulic conductivity of material surrounding a conduit or borehole, comprising the steps of: sealably fastening an end of a flexible liner to a proximate end of the borehole; passing the liner along the borehole while allowing the liner to evert at an eversion point moving through the borehole;

measuring the eversion point's velocity; and calculating the conductivity of the surrounding material from the velocity of the eversion point. The step of passing the liner preferably comprises driving the liner down the borehole, such as by pressurizing the liner with a fluid. The step of passing the liner also could comprise withdrawing the liner by inversion upward in the borehole, toward the proximate, or surface end of the borehole. An additional preferred step is monitoring tension due the weight and resistance of the liner ascent, particularly when practicing the invention by extracting or withdrawing the liner upward in the hole.

The step of calculating conductivity comprises determining a gross fluid flow rate outward into the surrounding material from the segment of the hole beyond the everting end of the liner. The method preferably comprises the further step of monitoring for changes in velocity of the eversion point, when the liner covers a flow path into a surrounding material, the gross fluid flow rate out of the rate is reduced by the amount of flow in the flow path covered, concurrently causing a change in the eversion point's velocity. The eversion point's velocity versus borehole depth can then be plotted to locate changes in conductivity associated with changes in eversion point velocity.

The invention also includes a preferred method of determining physical characteristics of materials surrounding a subsurface borehole, the borehole having at least some ambient water standing therein, comprising the steps of: sealably fastening an end of a flexible liner to a proximate end of the borehole; driving the liner down the borehole while allowing the liner to evert at an eversion point descending the borehole; continuously measuring the eversion point's descent velocity; determining a gross flow rate of the ambient water outward into the surrounding material from the segment of the hole beyond the eversion point of the liner. Driving the liner preferably comprises pressurizing the liner with a fluid. The method includes the further steps of continuously monitoring the pressure in the liner, and calculating conductivity from the gross flow rate outward into the surrounding material as a function of the liner driving pressure.

Preferably, the practitioner of the invention monitors for changes in velocity of the eversion point, wherein when the liner covers a flow path in a surrounding material, the gross fluid flow rate is reduced by the amount of flow in the flow path, concurrently causing a change in the eversion point's velocity. The step of plotting the eversion point's velocity versus borehole depth to locate changes in conductivity associated with changes in eversion point velocity may then be performed.

A primary object of the present invention is to provide a means and method for directly determining the hydraulic transmissivity or conductivity of discrete sections of the Earth's subsurface.

A primary advantage of the present invention is that it permits subsurface transmissivity to be measured comparatively quickly and with improved accuracy.

Other objects, advantages and novel features, and further scope of applicability of the present invention will be set forth in part in the detailed description to follow, taken in conjunction with the accompanying drawings, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating a preferred embodiment of the invention and are not to be construed as limiting the invention. In the drawings:

Fig. 1 is a side sectional view (of varying scale) of an embodiment of the present invention being practiced below the surface of the ground;

Fig. 1a is a sectional view (of varying scale) of an alternative embodiment of the apparatus shown in Fig. 1;

Fig. 2 is another sectional view of a preferred embodiment of the invention being operated in a borehole into the Earth's surface;

Fig. 3a is a graph showing qualitatively a hypothetical transmissivity profile that might be obtained by practicing the invention in a subsurface medium of uniform transmissivity;

Fig. 3b is a graph showing qualitatively a hypothetical transmissivity profile that might be obtained by practicing the invention in subsurface media of non-uniform transmissivity;

Fig. 4 is a diagram depicting certain geometric and hydraulic variables associated with the calculations used to determine transmissivity according to the present invention;

Fig. 5 is a graph, plotting velocity (ft/sec/psi) versus depth (m), showing a velocity profile measured from the bottom of a bore hole casing to the bottom of the hole; the raw data provides the ragged velocity profile (darker plot), while the normalized smoothed curve (the lighter curve, smoothed over a 40 second interval) is shown overlaying the raw data reduction;

Fig. 6 is a graph, plotting velocity (ft/sec/psi) versus depth (m), showing a monotonic curve (light-colored plot) overlaying the normalized curve from Fig. 5 (darker plot);

Fig. 7 is the log plot of a conductivity profile (lighter plot) determined from a series of straddle packer tests, and a (darker) plot of the mono conductivity deduced from measurements performed by the invention;

Fig. 8 is a log plot of certain packer-test conductivity data versus depth in meters;

Fig. 9 is an enlarged graphical depiction of an everting liner according to the present invention, shown in five different positions progressing down a bore hole past an irregular break-out or other expansion in the diameter of the borehole;

Fig. 10 is graph showing a conductivity profile generated by an actual down-hole field test of the present invention;

Fig. 11 is graph showing a conductivity profile generated by another actual down-hole field test of the present invention in a hole near the hole of Fig. 10;

Fig. 12a is a graph showing qualitatively a hypothetical transmissivity profile that might be obtained by practicing the invention in a subsurface medium of uniform transmissivity, when the invention is alternatively practiced by withdrawing an ascending everting liner out of the borehole, rather than driving the everting liner down the borehole;

Fig. 12b is a graph showing qualitatively a hypothetical transmissivity profile that might be obtained by practicing the invention in a subsurface medium of non-uniform transmissivity, when the invention is alternatively practiced by withdrawing an ascending everting liner out of the borehole, rather than driving the everting liner down the borehole; and

Fig. 13 is an enlarged radial cross section of a borehole with a primary liner installed therein and a secondary tube inflated to partially displace the primary liner.

DESCRIPTION OF THE PREFERRED EMBODIMENTS (BEST MODES FOR CARRYING OUT THE INVENTION)

Evaluating major flow paths from a hole is the main purpose of many geophysical measurements in boreholes. One method of assessing flow paths from boreholes is the use of straddle packers to isolate sections of the hole for measurement. Another method is the use of video cameras to examine fractures, if the water in the hole is sufficiently clear. Yet other techniques are used to assess the conductivity of the entire hole such as falling head slug tests or pumping tests.

The primary use contemplated for the invention is in subsurface boreholes drilled into the earth. However, the invention finds utility in pipes and conduits, as well. Throughout this disclosure and in the claims, "borehole" shall have a meaning including man-made conduits such as pipes and tubes, as well as subsurface boreholes.

The present invention uses an everting borehole liner to perform subsurface fluid conductivity measurements. The liner apparatus is similar in some respects to the device described in U.S. Patent No. 5,803,666, the disclosure of which is incorporated herein by reference. The present invention uses the everting liner in an innovative method for measuring certain subsurface characteristics. To "evert" means to "turn inside out," i.e., as a flexible, collapsible, tubular liner is unrolled from a spool, it simultaneously is topologically reversed so the outside surface of the tube becomes the inside surface.

In the present invention, the liner is everted into the hole, such as a vertical borehole for example, with pressurized fluid in the liner. As the liner displaces the ambient fluid in the borehole into the surrounding formation, the rate of descent of the liner is recorded. As the liner covers the flow paths in the wall of the hole, the descent rate slows. From the measured descent rate, the flow rates out discrete sections of the borehole are determined. This direct measurement of the characteristics of flow paths radially out from the borehole, by monitoring the descent rate of the everting liner, is a central facet of the present invention. Both the

hardware design and the method of analysis are described hereafter, and constitute aspects of the invention.

A leading advantage of the technique is that it requires less than 10% of the time for the typical logging or packer testing. Another advantage is that an impermeable liner often is installed in any event, for the purpose of simply sealing the borehole against flow. By the invention, data is collected at very little extra cost during the normal liner installation.

Generally characterized, the apparatus according to the present invention includes an encoder on a wellhead roller to measure the depth (versus time) of an everting liner. From the depth vs. time data the velocity of the liner's eversion point may be calculated. The apparatus also includes a means for continuously monitoring the driving pressure of the everting liner. The monitoring means may be a "bubbler" device of known configuration for monitoring the water level in the liner. Alternatively, pressure may be monitored by a simple pressure gauge for directly measuring the driving fluid pressure. In one embodiment, an additional component measures the tension exerted by the descending liner on a roller or spool at the surface. This tension measurement is a first-order correction to the conductivity inferred from the pressure and descent rate alone. In circumstances of a relatively deep water table, the tension measurement is essential to control any resistance to the liner's descent that is attributable to excessive liner tension. The tension measurement is very important if the conductivity measurement is performed during the extraction, rather than during the installation, of the liner in the hole.

The invention includes a method for performing measurements of subsurface characteristics. The use of the everting liner requires an analysis of the measured parameters to determine the transmissivity of discrete portions of the borehole. The process at the borehole may be succinctly described. The liner is inserted down the hole by driving it with a fluid pressure; it descends like a nearly perfectly fitting piston in the borehole. Above the everting end of the liner, the wall of the hole is effectively sealed by the liner. The liner's rate of descent

is used to calculate the gross fluid flow rate radially outward (into the surrounding subsurface regime) from the segment of the hole below the everting end of the liner. When the liner covers a comparatively significant flow path into the adjacent formation, the flow rate out of the open hole beneath the eversion point is reduced by the amount of flow in that path. The change in flow rate concurrently causes a change in the liner descent rate (velocity). A plot of descent rate versus depth shows the location of major flow paths by an associated drop in the descent rate at the location of the flow path.

Because the driving pressure in the liner is not necessarily constant, the conductivity calculation must include the driving pressure as a variable as well as several other important parameters such as the local "head" in the formation, the effect of any tension applied to the liner deliberately or through friction in the system, and other influential factors. The result is the distribution and magnitude of fluid conductivity (and thus permeability) of the subsurface geologic formations. The plotted results can be printed at the completion of the liner installation, using a computer and printer of off-the-shelf availability.

The inventive technique was used to deduce conductivity variations, relative to depth, in a vertical hole. The results from the invention were compared to conventional "packer test" results with very similar conductivity values. Notably, the conductivity profiler installation according to the present invention required about 30 minutes for these people to install to 300 ft. In contrast, the packer test procedure required 4 days for two people.

An advantage of the present invention is that an everting liner provides a continuous direct measurement of the location and flow rate of fractures and permeable beds intersecting the borehole. Since this is a direct measurement, there is no requirement for elaborate expert interpretation of the data. The procedure is relatively quick (e.g., from thirty minutes to about 1.5 hours for a complete profile of a 330 ft. (100m) hole). (The foregoing may be compared to the four days that likely would be required for a complete suite of straddle packer tests of the same hole.) Further, unlike straddle packers, with the present invention there is little

concern about leakage past the seal. The data set includes a continuous measurement of the transmissivity of the hole. Therefore, the integral of flow from the hole using the measured transmissivity values is internally consistent. Whereas, any leakage past packers (e.g., in a highly fractured or rough interval of the hole) leads to an upper limit rather than a real, or self-consistent, set of transmissivity values.

Reference is made to Fig. 1, illustrating the installation of a sealing liner according to the invention. Installation is easily performed by a field technician after very modest training. For the sake of clarity, in Fig. 1 the relative sizes of the sub-surface components of the invention are exaggerated relative to the sizes of components on the surface. Fig. 1 shows the initiation of the invention after the liner **10**, which is inside-out while wound around the spool or reel **20**, is clamped to the surface casing **22** at the upper or proximate end of the previously drilled borehole **25**. The borehole **25** is drilled into the subsurface, normally through the vadose zone **27** and to below the water table **28**. Consequently, the void of the borehole **25** below the water table **28** will tend to fill with ambient groundwater from the surrounding aquifer **29** or other, thinner, water-bearing strata. A short length of borehole **25**, in the vicinity of the ground's surface, is provided at its top or proximate end with the well casing **22** according generally to convention.

The thin-walled liner **10** is manufactured from a suitably durable, but flexible, collapsible, and impermeable plastic or composite. For example, liner **10** may be composed of urethane bonded to nylon. The liner **10** deployed according to the invention is selected to have a diameter generally corresponding to, but never significantly less than, the diameter of the borehole **25**.

The collapsed liner **10** is paid out from the rotating reel **20**, and preferably is passed over a guide roller **15**. The free end of the liner **10** is fastened and sealed to the proximate end of the casing **22**. The liner **10** is then progressively filled with driving fluid **30**, preferably water, introduced via above-ground fluid conduit **23**. As indicated in Fig. 1, the fluid is poured into

contact with the "outside" surface of the liner **10**, but as a result of the pressure of fluid **30** pushing the liner **10** down the borehole **25**, the collapsed tube of the liner is pressed against the walls of the borehole, resulting in the eversion of the liner. The eversion of the liner **10** occurs at a constantly moving eversion point **EP** as an ever greater length of the liner fills with driving fluid **30**. The former "outside" surface of the liner **10** effectively becomes the inside surface, as the water or other fluid **30** introduced from the fluid conduit **23** inflates and fills the liner thereby to press the former "inside" surface of the liner securely against the wall of the borehole **25**, as suggested by the darker directional arrows of Fig. 1. It is contemplated that the liner **10** is manufactured and disposed upon the reel **20** "inside out," so that the liner surface that eventually contacts the borehole wall initially defines the interior of the collapsed liner. As the borehole **25** fills with driving fluid **30**, the driving fluid nevertheless is continually contained within the inflated liner **10**, which impermeably lines the borehole above the downwardly moving eversion point **EP**. The liner **10** thus is passed along the borehole **25**, with the eversion point **EP** moving at some velocity.

As a result of, among other things, the rapid introduction of driving fluid via the conduit **23**, the driving fluid **30** fills the liner **10** to a driving fluid level **34** ordinarily somewhat above the vertical datum of the water table **28**, as suggested by Fig. 1. At any given point along the borehole column, therefore, the hydraulic head within the liner **10** somewhat exceeds the head attributable to ambient subsurface water, such as the pressure from the saturated aquifer **29**.

The pressure of the fluid **30** drives the liner **10** down the hole **25** somewhat like a piston. The flexible liner **10** under pressure, however, conforms to the irregular borehole wall, and does not slide on the borehole wall. With continuing forced introduction of driving fluid at the top of the borehole **25**, the liner **10** distends, elongates, and inflates toward the borehole wall. Again, the expansion of the liner **10** occurs at the eversion point **EP** where the liner is turning inside out, which point is at the lower-most point or annulus of the liner.

As noted, the borehole **25** below the water table **28** tends to fill with ground water **33** to a level approximating the vertical level of the water table **28**. As the liner **10** descends the borehole **25** under the pressure of the driving fluid **30**, however, it forces the standing water **33** from within the bore, through the borehole wall, and back into the surrounding strata **29**, as indicated by the lighter, convoluted directional arrows in Fig. 1. The displacement of the ambient water **33** by the driving fluid **30**, thereby to force the ambient water back across the borehole wall and into the surrounding geologic regime, is a central aspect of the operation of the invention. This "backflow" out of the hole **25** into the subsurface strata **29** allows the measurement of the hydraulic conductivity of that strata.

As the liner **10** propagates down the hole **25**, it seals the hole wall. The rate of descent of the liner **10** (i.e., the downward velocity of the eversion point **EP**) is controlled by the flow paths (convoluted directional arrows in Fig. 1) from the hole **25** into the surrounding strata **27, 29**. As the liner **10** descends, it covers the flow paths into the surrounding strata, and thus hydraulically isolates the upper portion of the hole above the eversion point **EP**. Consequently, the liner's rate of descent rate is dictated by the remaining fluid flow paths from the borehole below the liner's eversion point **EP**.

It is noted again that while this description of the invention refers to a "borehole" beneath the surface of the earth, the invention has practical utility in fluid transportation systems such as above-ground or structural pipelines. It is or will be readily evident, for example, that the invention can be used to detect and locate leaks in pipes.

Further understanding of the invention is obtained by reference to Fig. 1a, depicting an alternative embodiment of the invention seen in Fig. 1. In this embodiment, there also is provided a pair of pressure meters, **PM1** and **PM2**, for measuring the fluid pressure in the hole at locations below and above the eversion point **EP**, respectively. Thus by means of the first pressure meter **PM1** and a second pressure meter **PM2** the pressures below or above the point of liner eversion can be monitored. The pressure meters can be any suitable off-the-shelf

transducer. If both meters **PM1** and **PM2** are deployed, the pressure differential can be monitored and tracked as well. As explained further herein, it is preferable to have a means for measuring at least the pressure above the eversion point **EP**, if not below the eversion point, for practicing the invention.

Reference is made to Fig. 1, showing a liner **10** that has progressed a significant distance down the hole **25**. The liner **10** preferably controllably unwound from a reel **20** and is passed over a roller **5**. The roller assembly **5** is equipped with tension and position metering devices **M**, known in the art, for measuring the amount (length) of liner **10** that has been paid out, as well as for gauging the tension in the down-hole liner due to gravity. Thus, the meter **M** includes an encoder, in operative connection with the axle of the wellhead roller **5**, to measure the depth of the everting liner in time. Additionally, by constantly monitoring the tension in the liner **10**, the absolute driving pressure of the fluid within the liner can be ascertained, with the tension force providing a correction factor. The metering equipment collected in component **M** also includes a means for monitoring continuously the driving pressure of the everting liner. This driving pressure monitoring means may be a "bubbler" for monitoring the driving fluid level **34** within the liner **10**, or a simple pressure gauge (such as pressure meter **PM2** in Fig. 1a) for directly measuring the driving pressure. Further use of the metering devices **M** in an alternative manner of practicing the invention will be explained later herein.

When first inserted at the surface casing **22**, the liner **10** starts with a maximum descent rate. The descent rate is dependent upon the rate at which the ground water **30** is forcibly displaced radial outward into adjacent subsurface formations by the descending liner **10**. Each time the unwinding liner **20** covers a significant flow path into an adjacent stratum, for example the sand lens **37** seen in Fig. 2, the liner's descent slows by an amount dependent upon the flow path thereby sealed. Stated differently, passing a large open fracture in a subsurface formation (e.g. within a layer of the saturated zone **29**), or passing a stratum of high permeability, causes a large drop in the liner descent rate.

A plot of the liner descent rate, in a hypothetical uniform conductivity medium (e.g., homogenous sand) is shown in Fig. 3a. It is a straight line, indicating that the rate of liner descent (the rate at which the point of eversion descends the borehole) is generally decreasing at a constant rate to the total depth (TD) of the bore. The slope of the line suggests the conductivity of the medium, with steep slopes suggesting high conductivity. In contrast, in a fractured medium or layered media, the descent velocity versus depth is non-uniform, and the plot of descent rate versus depth may look, for example, like Fig. 3b. The velocity drops in abrupt steps (a large fracture) or a sloped step (a permeable zone). Constant velocity intervals are regions of little water loss from the hole. In the example of Fig. 3b, four zones of extremely high conductivity are indicated by abrupt increases in the slope of the plot line at f1, f2, f3, and f4. Such abrupt and abbreviated plot segments are generally associated with fractures, or perhaps thin lenses of course sand, exhibiting high conductivity. The intervals having a shallow slope, such as those at t1, t2 and t3 on Fig. 3b, are indicative of "tight" geologic formations, zones of comparatively low conductivity. Portions of the plot manifesting moderate slopes, such as at p1 and p2 on Fig. 3b, correlate to comparatively permeable subsurface formations; the steeper the plot slope, the higher the conductivity of the corresponding formation.

At the total depth of the borehole ("TD" on Figs. 3a and 3b), the liner reaches the bottom of the hole and its eversion stops. Further, it is apparent to one skilled in the art that the vertical thickness of a particular subsurface layer of particular conductivity may be determined by reference to data on the "depth in hole" axis of the plot. The graphs of Figs. 3a and 3b are generally qualitative in character for purposes of illustration. In the practice of the invention both the domain and the range are plotted numerically to enable quantitative evaluation.

The inventive technique thus deduces from the liner's velocity profile the flow characteristics of each flow path sealed by the liner **10** as it descends vertically, by measuring the descent rate and the driving pressure in the liner (i.e., the excess load or water level **34** inside the liner **10**).

An alternative use for the invention is to measure the velocity of an ascending liner. The liner motion is reversed by pulling upwards on the inverted liner **10** at the top of the hole, and the resulting motion is indicated by a solid, straight directional arrow in Fig. 2. The principles of the alternative method are essentially the same as with a descending liner, simply approached from a "reversed" perspective. Fig. 2 shows the apparatus of the invention deployed for ascending liner methodology. A liner **10** progresses a significant distance up the hole **25**. The liner **10** preferably controllably wound upon a reel (not shown in Fig. 2) and is passed over a roller **5**. The roller assembly **5** is equipped with tension and position metering devices **M**, known in the art, for measuring the amount (length) of liner **10** that has been paid out or reeled in, as well as for gauging the tension in the down-hole liner due to gravity. Thus, the meter **M** includes an encoder, in operative connection with the axle of the wellhead roller **5**, to measure the depth of the everting liner in time. The metering equipment collected in component **M** also includes a means for monitoring continuously the driving pressure of the everting liner. This driving pressure monitoring means may be a "bubbler" for monitoring the driving fluid level **34** within the liner **10**, or a simple pressure gauge (such as pressure meter **PM2** in Fig. 1a) for directly measuring the driving pressure. Further use of the metering devices **M** in an alternative manner of practicing the invention will be explained later herein.

In the alternative method of an ascending (inverting) liner, the liner **10** is caused to invert as the central portion of the liner rises. The driving force is the tension on the liner. As the liner inverts and rises in the hole, water is drawn into the hole beneath the inversion point **EP**. The liner velocity can be measured by drawing the liner over the same roller. An alternative mode is to measure the flow rate out of the liner at the top of the casing **22** as the water spills over the top of the liner **10** as it is inverted. Fig. 2, for example, shows a flow meter **FM** for monitoring the fluid flow discharge from the ascending liner. The inversion causes the interior volume of the liner **10** beneath the surface pipe to decrease. The flow out of the liner **10** equals the flow into the hole **25** beneath the inversion point. The flow measurement has the advantage that it is not affected by the stretch of the liner **10** nor by the variation of the diameter of the borehole **25**. The velocity of the liner **10** over the roller **5** is affected by only a small error

due to stretch of the liner under varying tension forces. The method determining conductivity using an ascending liner thus preferably includes a step of measuring the flow rate of fluid produced from the top end of the liner, as well as monitoring tension in the liner itself.

The driving force of the ascending liner **10** is the tension on the liner. The pressure in the hole **25** beneath the ascending liner is dependent upon the tension in the liner as it rises. However, the pressure inside the liner **10** also affects the tension measured at the surface in the liner. Measurement of either the head in the liner, or the fluid pressure in the liner, coupled with the tension of the liner allows the deduction of the pressure in the hole **25** beneath the liner **10** according to the simple approximation:

$$\text{Tension} = \text{A (Pressure inside the liner} - \text{the pressure outside the liner)/2}$$

where A is the sectional area of the expanded liner (see A_Z in Fig. 4).

From this relationship, the pressure outside the liner **10** in the hole **25** beneath the liner can be calculated. An increase in the tension will lower the pressure in the hole **25** beneath the liner **10**. As will be shown later, the upward velocity of the liner will increase with increased tension, but the rate of rise is still controlled by the flow rate into the hole beneath the inversion point.

In this manner, for an ascending liner, one can deduce the transmissivity of the borehole **25** beneath the liner in a manner similar to that for a descending liner.

The invention uses an off-the-shelf liner **10**, but adds the measurement of velocity (distance and time) to the roller **15**. The water flow out of the liner is monitored continuously, for example by means of a flow meter **FM** gauging the discharge from within the liner **10** at its top end. (Fig. 2) Data regarding the ascent rate and deployed length of the liner **10** (from

meters **M** associated with the roller **15**) and regarding the discharge from within the liner (from meter **FM**) are recorded on a conventional high-speed lap top computer as the liner is installed or removed. The data reduction is performed digitally in the computer as the data is collected. When the liner **10** reaches the top of the hole **25**, the plot of the conductivity profile can be printed.

For deep water table installations, the hanging weight of the liner **10**, especially for segments of the liner free-hanging in the vadose zone (**27** in Fig. 1), and any additional restraining tension also is measured by meters **M** and recorded to calculate the proper conductivity profile. In areas having a very deep water table **28**, it may be desirable to blow air into the liner **10** to inflate it against the walls of the borehole **25**, thereby reducing the friction of the inverted liner against the liner pushed against the bore hole wall (the everted liner).

The actual results are measured as changes in the transmissivity of the wall of the hole **25** correlated to the descent or ascent of the liner **10**. Given the length of the increment of the hole measured, effective conductivity is calculated. This can be related to an effective fracture aperture if the number of fractures is known.

The method described above for a descending liner is the usual mode of use. The ascending liner technique has the additional necessity to measure the tension on the liner above the hole. The ascending liner procedure is most useful, however, for liners which have been emplaced beneath the surface and filled with water as described in the prior U.S. Patent No. 6,298,920. This installation uses a push rod (also called a rigid casing). Once the rod is removed, the liner is left filled with water to above the surface. A tube connects to the bottom end of the liner for the purpose of inverting the liner from the hole. As the tube is withdrawn from the hole, the inverting liner connected to the tube is also withdrawn. The same procedure and data reduction for the ascending liner apply. The advantage of this technique is that a stable open hole is not required. The internally pressurized liner is usually adequate to stabilize an otherwise unstable in unconsolidated sediments. Since the liner emplaced via push rods has

another purpose, the removal procedure performed and measured as described adds additional utility to the liner installation.

In all descending liner embodiments of the invention, the liner forces the ambient ground water into the surrounding formation because of the excess head in the liner. The excess head in the liner is measured relative to the head in the formation. An initial assumption in this invention is that the head in a subsurface formation is uniform. When the head profile in the formation becomes known, the assumption of a uniform head in the formation can be corrected to the actual head as needed. However, the driving pressure in the liner (excess head) usually exceeds substantially the natural head in the formation.

Another assumption underlying the invention is that the water flow from the hole below the liner is radial, essentially horizontal and one dimensional. This approximation is not particularly significant to the utility of the invention. As the liner descends, it seals, sequentially, the flow paths from the hole with a resulting drop in the liner descent rate. It is assumed that the flow from the hole is steady state. Since the gradient near the hole wall, which dominates the flow, develops relatively quickly, this is not a significant limiting assumption. In practice, the liner descent is relatively continuous with very few stops.

A third legitimate assumption is that the flow rate out of the hole is equal to the descent velocity of the liner multiplied by the cross section of the hole. The hole cross section may not be constant, the effect of cross section variations with depth can be addressed in the analysis.

Finally, it is assumed that the liner either everts with very little frictional resistance or the eversion resistance is corrected by a small adjustment in the driving pressure. Since the liners have been very well tested, the correction is small and reliable. Other forms of friction, drag, buoyancy, etc. are addressed further hereinafter.

A model for performing data reduction according to the present invention is shown in Fig. 4, which depicts the geometry of the calculations used in the invention. Z is the distance down the borehole. The liner descent may be compared to a perfect-fitting piston. The radial flow (Qr) out of the hole is approximated by a one-dimensional flow field obeying Darcy's law:

$$Qr=Ar\ Vr = 2\pi\ r\ H\ K/\mu\ \ dP/dr$$

where Ar is the radial flow area traversed by velocity Vr. H is the height of the radial flow area, K is the medium permeability, μ is the viscosity of water, and dP/dr is the pressure gradient.

Separating variables and integrating gives:

$$\ln(r_o/r_a) = 2\pi HK(Pa-Po)/(\mu Qr)$$

where r_0 is the hole radius and r_a is the range to ambient pressure, Pa. Po is the pressure in the hole. Po>Pa. Qr is the radial, horizontal flow out from the hole. The flow out of the hole should equal the rate at which water is being displaced downward by the liner. That is, Qr =Qz. where Qz is the vertical flow rate. The vertical displacement by the liner is: $Qz = Az\ v_z$, where (Az) is the cross section of the hole and v_z is the liner descent rate. By measuring the liner descent rate, v_z is known. A caliper log provides $Az = \pi\ r_o^2$ as a function of the hole depth. A very useful result can be obtained by assuming that r_0 is a constant.

It is noteworthy that there is no reason to expect the liner descent to be other than a monotonic decreasing velocity history. Therefore:

$$Qr = Qz = 2\pi HK(Pa-Po)/(\mu\ \ln(r_o/r_a)$$

Solving for K provides the effective conductivity of the entire open hole below the liner. This is a useful result, but not a profile of the hole.

A central aspect of the inventive conductivity profiling technique is to assume that as the liner descends, it will cover flow paths, resulting in a change in Qz as reflected in v_z or,

$$Qz(z_i) - Qz(z_{i+1}) = \delta Qz_i = \delta v_{zi}\ Az_i = \delta Qr(z_i \text{ to } z_{i+1})$$

$$= -2\pi\ \delta z_i\ K_{zi}(Po\text{-}Pa)/(\mu\ \ln(r_o/r_a)$$

K_{zi} is the permeability of the interval $\delta z_i = z_{i+1} - z_i$,

covered by the liner during time interval $\delta t_i = t_{i+1} - t_i$.

Solving for the permeability of the interval, $K_{zi} = \delta v_{zi} A_{zi}\ \mu\ \ln(r_o/r_a)/(-2\pi\ \delta z_i(Po\text{-}Pa))$

The important parameter, $\delta v_{zi}/\ \delta z_i$, is determined from the recorded data. The "i" subscript is introduced because of the time and distance discrete collection of the data. The smoothing of the data and proper centering of the variables is part of the data reduction done by a computer program written for that purpose, a task within the skill of the known programming arts.

Another factor in the actual measurement of a descending liner is that the tension on the liner **10** is not zero. The tension must be adequate to support the liner above the water level (**34** in Fig. 1) in the liner. Any excess tension will reduce the driving pressure of the excess head.

Notably, installation of an everting liner will progress more rapidly in subsurface regimes of high transmissivity. However, in formations of low transmissivity, installation

necessarily will progress slowly, because the invention provides a method of directly measuring transmissivity. If the velocity descent goes to zero before the total depth is obtained, then the near-impermeability of formations below the zero-velocity level may be inferred.

It is apparent to one of ordinary skill in the art that the measuring method of the invention may be performed using the ascending, rather than descending liner technique. The principles and mathematical equations are generally the same; they are simply applied while the liner **10** is being extracted from, rather than installed into, the hole **10**. A transmissivity profile may be generated using the system shown in Fig. 2, where the powered reel is used to pull the liner **10** from the borehole while monitoring the tension the liner exerts on the roller **15**. In this alternative mode of practicing the invention, the tension in the ascending liner above the point of eversion **EP** is the main driving force. It thus is essential to use the metering equipment **M** associated with the roller **15** to continuously measure the tension in the liner as the liner is taken up and wound around the reverse-powered reel. The excess head (difference in the head of the fluid **30** and the standing ground water **33** must also be closely monitored and logged. By measuring tension versus the liner's ascending velocity, the conductivity profile can be determined during the withdrawal of the liner, as native ground water flows into (as opposed to out of) the bore hole **25** below the everting liner **10**, as indicated by the convoluted directional arrows in Fig. 2.

Figs. 12a and 12b are qualitative graphs showing hypothetical plots of liner ascending velocity versus hole depth in an "ascending liner" measurement. Fig. 12a is analogous to Fig. 3a, and suggests what the graph generated by a liner ascending through a homogenous or uniformly permeable medium might look like. Fig. 12b offers a graph analogous to Fig. 3b, and provides a hypothetical plot generated by a liner ascending through several strata of differing transmissivity. Like Figs. 3a and 3b, the abrupt and steep segments of the plot are indicative of permeable zones or fractures, while shallow slopes suggest tighter formations.

Reference is made to Fig. 13. The use of an ascending liner eversion point to measure transmissivity during liner withdrawal may be eased by the use of a secondary tube **40** installed parallel to the main liner **10**. The secondary tube **40** is originally co-installed in advance of, or with, the liner **10**, but not inflated in any way; when the liner **10** is reeled toward the surface for de-installation, the secondary tube **40** is inflated with any suitable pressurized fluid, thus pushing aside the liner **10** as seen in Fig. 13. As the liner **10** shifts aside, fluid flow paths **41** are opened to allow water to flow in during liner withdrawal.

It is noted that the secondary tube **40** may be placed, but is not inflated, during the descent of the main liner **10** while a measurement is being made. The secondary tube **40** is inflated during removal (ascent) only to speed the ascent) of the main liner when no measurements are being performed, thus providing the practical benefit of rapid de-installation of the apparatus.

A small secondary tube **40** or liner also may be useful for the descending liner technique. The descending liner uses an additional device to aid the withdrawal of the liner after the measurement has been completed. In a relatively low permeability formation, the liner installation may require several hours or more to descend to the bottom of the hole. The removal of the liner is performed by pulling upward on the inverted liner, or a cord attached to the closed end of the liner. The inflow into the hole may be very slow and hence the liner removal may require a time as long as the installation required. In order to greatly reduce the removal time, a small diameter, empty, flat liner (Fig. 13) can be lowered into the hole prior to the liner installation. The small liner may be (but is not necessarily) closed at the bottom end and open at the top end. The liner installation and transmissivity measurement is unaffected by the flat , collapsed small liner. The inflated liner seals well against the flat small liner.

Prior to removal of the large liner by inversion, the small liner is filled with water to dilate it to a nearly circular cross section (Fig. 13). This opens an interstitial space **41**between the liner **21**, the hole wall **25**, and the small liner **40**. The interstitial space serves as a

conductive path to flow paths in the formation high above the eversion point. This allows water to flow more quickly from the formation into the hole beneath the ascending liner. In that manner, the liner can be raised much more quickly from the hole than if there were no such connection to flow paths above the eversion point. The small liner is not necessary to perform the measurement that is the substance of this invention, but it allows the measurement to be performed in a reasonable length of time.

The invention may also find use in evaluating the flow field in the media between the borehole **25** and any nearby monitoring wells. As conductivity profiling is being performed according to the invention as described, the installation of a descending liner produces a line pressure source of decreasing length in the borehole **25**. Monitoring the effect of the line boundary condition in nearby monitoring wells may offer insight into the flow field between the hole **25** with the descending liner **10** and the monitoring holes nearby. The position of the liner **10** and the driving head in the liner are measured as a function of time. The liner **10** can be driven, in this instance, as fast as needed with a gravity water supply, and the decreasing line source gives more special resolution than an entire pumped well. Further, there is no concern about a bypass of the liner providing a spurious "source." The liner **10** can be inserted at a measured head and removed with a measured head and a measured tension (equals a measured drawdown).

Thus, an alternative is offered to simply pumping on a single hole to develop a boundary condition, or doing packer interval extractions to test the flow field to the monitoring wells. Modern modeling techniques can then reproduce the decreasing line source for assessment of the data obtained in the monitoring well(s) and the implied flow field in the area as driven be the descending (or ascending) liner **10**.

Industrial Applicability:

The invention is further illustrated by the following non-limiting example.

A conductivity profiling system generally in accordance with the foregoing disclosure was implemented and tested. The first data collected was the observation that the descent rates of blank liner installations were highly variable for different holes and sometimes changed abruptly. The velocity of tape marks on the liner gave flow rates into the formation. When the applicant built "linear capstans" for liner removal, they were instrumented to measure tension of the liner and depth with time. Then digital recording was added to collect the data. Bubblers were used to monitor the water level inside the liner to determine the excess head in the liner.

An early experimental test of the method was performed at Cambridge, Ontario, for the University of Waterloo. A linear capstan was coupled with laptop computer recording to measure the parameters in the equation herein above. The parameters not measured were hole diameter, and the range from the hole to a known pressure (Pa to r_a). (If Pa is defined as the ambient pressure, and r_a is estimated (guessed), the error in the $\ln(r_o/r_a)$ is not large relative to the much larger range of conductivity for the formation.)

An advantage of the University of Waterloo installation was that a complete set of packer tests had been done on the 330 ft, 6 in diameter hole. The comparison of the inventive profiler with the Waterloo data is shown hereafter. The packer testing required 4 days to perform. The measurement by the inventive method required about 1.5 hours, including set up.

The velocity profile measured from the bottom of the casing to the bottom of the hole is shown in Fig. 5, a plot of velocity (ft/sec/psi) versus depth (m). The raw data provides the ragged velocity profile (darker plot in Fig. 5). The occasional drops to a zero or near zero velocity are due to operational pauses in the installation. Those can be ignored, but they do affect the smoothed velocity curve. The normalized smoothed curve (the lighter curve, smoothed over a 40 second interval) is shown on top of the raw data reduction. As explained

further hereafter, the expansion of the liner into an incidental enlargement of the hole caused the liner descent rate to slow due to the increased cross section of the hole. This obviously was not related to flow out of a fracture. As the hole diameter returned to its normal diameter at a lower elevation, the liner speed recovers. To overcome this effect, a monotonic decreasing curve was fit to the velocity data to extrapolate over the dips in the velocity curve.

The monotonic curve is shown as a separate light-colored curve in Fig. 6 with the smoothed curve from Fig. 5. This monotonic curve is used to distribute the transmissivity of the hole in the proper regions. If the monotonic velocity curve is normalized (as illustrated by Fig. 6) to the maximum value (the initial velocity value), the curve is a plot of the fraction of the flow remaining in the hole below the liner as a function of the liner depth. The sharp drops are an indication of the flow lost as the liner descends and covers the flow paths.

Fig. 7 is the log plot of the conductivity profile measured by the series of straddle packer tests. Conductivity (K), in cm/sec, is plotted for packer tests on the vertical axis versus depth below surface (meters) on the horizontal axis. The mono conductivity deduced from measurements performed by the invention is plotted on the same graph. Some of the large packer values are lower conductivity zones as measured by the invention. This may be due to packer leakage.

Fig. 8 is a log plot of the packer data with depth in meters. It is noteworthy that the straddle packer tests average the apparent flow over the measurement interval of the packer. That is not quite the same as the liner velocity measurement. Yet the large flow paths clearly occur in the same parts of the hole.

It is noted that the comparison of the invention testing with packer tests is not a test of the model, except that there should be a correlation of high and low flow zones. Packer

isolation of a segment of the borehole depends upon the packer seal to the hole wall and the connection between the isolated interval via the medium (e.g., fractures) to the hole above or below the pair of packers.

Commonly installed packers nearly always leak more or less. In highly fractured zones, the packer pair will probably leak a great deal. In tight sections where the hole wall is likely to be smooth, and the flow paths past the packer are less likely, the amount of leakage is probably small, even though it may still be a large fraction of the flow into the medium. The result is that a complete series of packer tests (i.e., the entire hole is measured) will predict a total flow greater than that into, or out of, the medium in a whole hole transmissivity test. The integral of the packer test is an upper bound on the flow capacity of the entire hole. Packer tests are often done with measurements of pressure above and below the packers for detection of leakage.

In the operation of the invention, however, there are two distinct segments or portions of the borehole **25**: the sealed section above the point of eversion **EP**, and the unsealed hole below the point of eversion. As the liner **10** descends, it will not seal an extremely rough hole wall or a breakout larger in diameter than the liner **10**. In such an instance, there is upward flow to horizontal flow paths above the evasion point **EP**. However, when the point of eversion **EP** reaches a section of hole which can be sealed, the leakage is stopped between the unsealed and the sealed portion of the hole **25**.

In the situation just described, the integral of flow from the hole **25** is correct. The error introduced by an imperfect seal of the hole **25** is to compress the hole conductivity of the unsealed portion of the hole (if there is any conductivity in that portion) into the zone immediately above the well-sealed segment of the hole. Reference is made to Fig. 9, showing a sequence of liner positions as the liner **10** descends (everts) through a "breakout" in the borehole or other hole enlargement **39**. At position **A1**, the liner diameter matches the nominal diameter of the borehole **25**. At **A2**, the liner dilates into an enlargement. At **A3**, the liner is at its maximum size, which is less than the breakout diameter. At **A4**, the liner is again sealing the

hole at less than the liner's maximum diameter. Finally, at position **A5**, the liner **10** is back to the nominal diameter of the borehole **25**.

Between positions **A2** and **A4**, the liner **10** is not sealing the hole **25** and flow can continue out of the breakout **39**. For that short interval, the assumption that the flow occurs only out of the hole below the liner's point of inversion is violated. In that interval also, the velocity will not change with depth. At **A4**, the flow into the breakout **39** is stopped and the liner may see an abrupt drop in velocity. If there is no flow out of the breakout **39**, there will not be a drop in the liner velocity at **A4**.

Another effect of the hole diameter not being constant with depth is discussed here. Non-uniform diameter of the hole **25** causes a decrease in the liner descent rate as the liner **10** dilates into the larger diameter (e.g., **A2-A4** in Fig. 9). Such an event could be interpreted erroneously as a permeable interval covered by the liner. However, when the hole converges (**A5**), the liner velocity increases (a contradiction of the expectation of a monotonically decreasing velocity as flow paths are covered). The reason for the velocity change is that $v_z = Qr/Az$. If Qr, the radial flow out of the hole is constant, v_z is inversely proportional to $Az = \pi r_0^2$ A small change in r_0 can change the velocity significantly (e.g., a radius increase of 10% is a 20% area and velocity change). If a caliper log is available, the correct diameter can be used in the model.

Such variation of v_z is addressed by ignoring temporary dips in the velocity versus hole depth curve. The effect of the model is to compress any real flow path conductivity into the lower portion of the enlarged interval (Fig. 9 at **A4**), because that is where the descent velocity will drop due to any loss into the breakout **39**. The model, and the measurement, will recognize the difference between the velocity at **A1** and **A5** due to flow into the breakout.

These two potential perturbations of the conductivity profile inferred from the data will cause shorter regions of conductivity higher than the actual value, but the total fracture or

permeable bed flow capacity is conserved. Therefore, the inventive apparatus and method results may produce some short spikes for enlarged regions that may be better measured by ordinary packers, if the packers are located so as to straddle a permeable breakout zone bounded by impermeable zones at the packer locations.

The ability to measure packer leakage in the hole above or below the straddle packer depends upon the transmissivity of the hole above or below and the pressure developed between the packers. However, the generalization that packers produce only an upper bound on reality seems to be valid. Also, the generalization that a descending liner is measuring relatively correctly the transmissivity of the hole below the liner seems to be valid.

A potentially better test of the invention, but one which has not been conducted, would be a vertical flow meter map of a heavily pumped hole. However, in such a test the hole must be pumped with a draw down that overwhelms the natural head at any place in the hole.

Experience has shown that the higher the head driving the liner, the better is the data quality, because the small perturbations do not affect a relatively high velocity of installation. However, for very permeable holes, it requires a relatively large flow rate for the water addition to maintain a substantial head.

For holes with relatively low conductivity, the water addition can be relatively slow, but the difficulty is that the liner descent rate can be so slow that the entire traverse can not be done in a reasonable time (e.g., a few hrs to a day). Since the liner descent always slows, it may also be that a measurement is practical in only the upper portion of the hole where the velocity of descent is greater. Fig. 10 shows a profile taken in a hole with most of the conductivity between 40 ft (from the bottom of the surface casing) and 63 ft. By that depth, 92% of the effective flow paths had been passed. The installation was terminated at 116 ft of a 190 ft hole because the descent rate was so slow.

In contrast, another profile, shown in Fig. 11, taken in a nearby hole shows that approximately 35% of the hole flow was out of a fracture pair only 3 ft above the bottom of the hole. This installation went easily to the bottom at 185 ft.

Accordingly, the installation of a blank liner to seal the hole to be tested offers the capability of determining the conductivity profile of the subsurface regime. The measurement of the liner's descent rate can provide useful information about the distribution and capacity of the flow paths out of the borehole. Effects of borehole diameter variations, ruguosity, and fractures in the formation have much less effect on the liner measurement than they have on the measurements performed with a complete suite of straddle packer tests.

Advantageously, the invention offers a relatively direct measurement of the distribution of the flow paths in the borehole. Conventional geophysical measurements are very indirect measurements of the possible flow paths from a borehole (although flow meter and temperature measurements are exceptions to the generalization). Further, the inventive method generates conservative results; it always closes leakage around the liner due to borehole irregularities once the point of eversion reaches the next undisturbed (nominal diameter) portion of the hole.

The preceding examples can be repeated with similar success by substituting the generically or specifically described reactants and/or operating conditions of this invention for those used in the preceding examples.

It also is immediately apparent that the invention may find practical utility in various types of conduits other than vertical bore holes. For example, the inventive technique may be employed to test for and locate leaks in conventional pipes. The method can be practiced in non-vertical bore holes. The liner alternatively can be driven by air or other fluid besides water. And, a person of skill in the art of hydraulic engineering could perform an assessment of head profiles by halting, then reversing, the descent of the liner.

Although the invention has been described in detail with particular reference to these preferred embodiments, other embodiments can achieve the same results. Variations and modifications of the present invention will be obvious to those skilled in the art and it is intended to cover in the appended claims all such modifications and equivalents. The entire disclosures of all references, applications, patents, and publications cited above are hereby incorporated by reference.